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Determination of the elastic modulus of fly ash-based stabilizer applied in the trackbed

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Abstract. This paper describes a unique application of a fly ash-based stabilizer in the trackbed of a railway main line. The key goals of the stabilizer application are to protect the subgrade against the ingress of rain water, to increase the frost resistance and to remediate the natural ground constituted of weathered rock. The stabilizer was designed as a mixture of fly ash, generated as a waste material from coal plants, gypsum, calcium oxide and water. The mixture recipe was developed in a laboratory over several years. In 2005, a trial section of a railway line with subgrade consisting of clay limestone (weathered marlite) was built in the municipality of Smiřice. Since then, periodical measurements including collection of samples for laboratory evaluation of the fly ash-based stabilizer have taken place. Over the time span of the measurements, changes in mineral composition and development of fly ash transforming structures leading to the formation of C-A-S-H gel were detected. This paper describes the experimental laboratory investigation of the influence of dynamic loading on the elastic modulus of fly ash stabilizer samples and the development of permanent deformation of the samples with increasing number of loading cycles.

1. Introduction

Trackbed is an integral part of a railway track structure, designed to and maintained in such a state that it can preserve the line and the level of a railway track. It provides support for sleepers of the track and prevents the failure of the structure due to excessive settlement or shear failure on the formation or subgrade level. In a conventional track structure, trackbed consists of a ballast layer and additional optional trackbed layers. The additional layers are introduced into the trackbed system for two main reasons. First reason is mechanical and is applied when the bearing capacity of subgrade soils is not high enough to support the ballast layer. Various materials can be utilized for the layers with blanketing sand or crushed aggregate/engineering filling being the most common [e.g., 1,2]. Second reason relates to the influence of climate on subgrade soils. At some instances, the mechanical strength of subgrade soils is sufficient to provide the required support but the soils are susceptible to either the ingress of the surface water or the effect of frost cycles or both. In such cases, the trackbed layers might be introduced to insulate the subgrade soils against the water ingress and against the low temperatures. It can be seen that ‘traditional’ trackbed layer materials as sand or aggregates are usually permeable, i.e. cannot be used as an insulation against the water ingress. Also, the thermal conductivity of sands/aggregates is quite high, which may result in a high required thickness of the trackbed layers if these materials are to be used as thermal insulators [e.g., 1, 3, 4]. To overcome the above stated disadvantages of sands/aggregates, some standards allow for the design of a protective layer made of concrete or asphalt or the usage of geosynthetics [e.g., 1]. While such solutions clearly provide impermeability against the water ingress and usually fulfil the thermal insulation requirements as well, their disadvantage is high cost. Hence, there has been an effort to investigate the possibility of introducing a new construction material for trackbed layers which could provide sufficient water and thermal insulation while reducing the costs required to build the layer.

Part of the research into the new trackbed material has been conducted at the Czech Technical University in Prague. As soon as 2005, Lidmila [4] investigates the possibility of introducing a trackbed layer made of fly ash (pulverised fuel ash) to protect subgrade consisting of clay limestone (weathered marlite) during the reconstruction of a main line track in Smiřice station, Czech Republic. The proposed solution was approved and a unique application of a trackbed stabilizer made of fly ash was built in April 2005. Since 2005 to 2011 and then again from 2014, periodic biannual investigations are conducted on the site. The investigations consist of in-situ Plate Load Test measurements and sampling for further laboratory investigations, e.g., compressive strength, reference density. Details and a summary of the first ten years of the research can be found in [3, 5, 6].

Since the beginning, the research has focused on time-related changes in the material properties of the fly ash layer, e.g. changes in compressive strength, changes in reference density, water regime of the layer in reference to weather seasons and microanalysis of the material. However, recently the research has been expanded to include the behaviour of the material under dynamic loading. The research extension seeks to accomplish two main aims. Because no methodology for dynamic investigation of trackbed materials is currently adopted in the standard system of the railways in the Czech Republic, the first aim has been to develop a suitable methodology for the investigation. The second aim has been to investigate the changes in elastic modulus and the evolution of permanent deformation of the fly ash material under cyclic loading.

This paper presents the methodology adopted for the research along with some preliminary results. The adopted cyclic loading sequence is discussed and results for a representative sample of the fly ash material under the loading are shown. The changes in the elastic modulus and the evolution of permanent deformation with the increasing number of loading cycles are discussed.

2. Methodology

The investigation of the behaviour of the fly ash material was based on laboratory experiments performed on samples extracted from the fly ash trackbed layer. The samples were obtained by core drilling from the layer during the biannual visits in Smiřice. Details of the sample collection can be found in Lidmila & Lojda [5]. After performing the cyclic loading experiment described here, the samples were subjected to a destructive compression strength test. For this reason, sample collection and preparation followed ČSN EN 13286-41 [7] and ČSN EN 13286-43 [8] as closely as practicable.

As mentioned above, because no agreed-on methodology currently exists in the railway standards system in the Czech Republic, the methodology developed for the presented research combines cyclic loading sequences adopted from resilient modulus testing with the laboratory instrumentation adopted from the testing of the elastic modulus. Both parts are described in detail below.

2.1. Loading function

For cyclic loading function, it was intended to subject the material to a loading as close to real traffic loading as reasonably practicable. Details about this problem and review of its solutions can be found e.g. in Brown [9]. Nowadays, suggestions for a cyclic loading function sufficiently close to the real traffic loading are included for instance in BS EN 13286-7 [10] or AASHTO T307 [11]. In terms of frequency and loading shape, AASHTO T307 suggests a loading sequence consisting of a half-sine impulse with the duration of 0.1 s followed by a 0.9 s long period of zero loading. Such loading sequence corresponds well with the real traffic loading under intermediate speeds (70-100 km/h) [e.g., 9]. However, due to the limited sampling rate of the data logger used (see below) the loading sequence adopted for the presented research had to be changed into the form as presented on Figure 1. Also, the loading frame used (see below) requires minimum 'seating force' of 0.2 kN to be applied all the time.

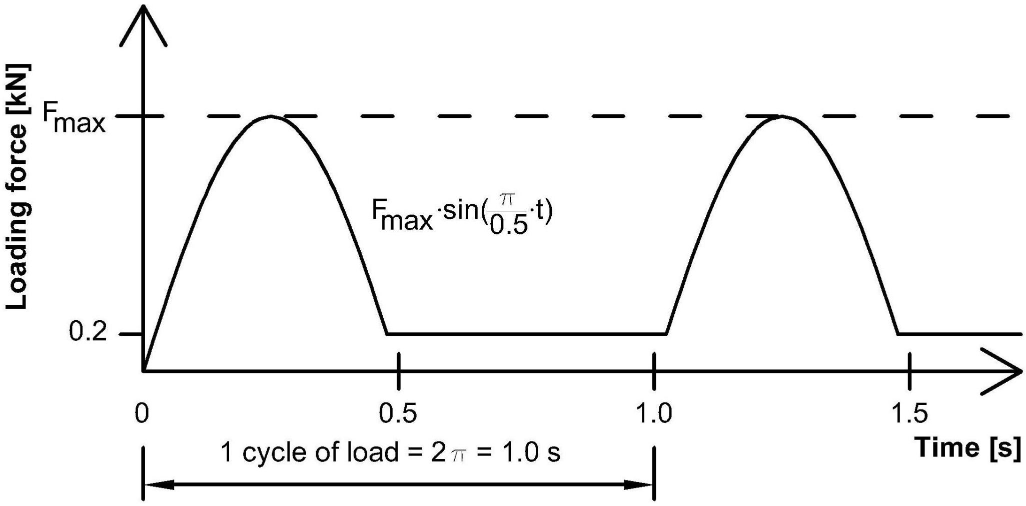

Figure 1. Adopted cyclic loading sequence for the laboratory experiment.

In terms of the maximum load per cycle and the number of loading cycles, BS EN 13286-7 suggests to apply load in five equal steps and to perform 100 cycles in each loading step. However, the primarily focus of the BS standard is on testing of soils in a triaxial apparatus. Hence, the suggested maximum load values were too small to be applicable for the presented research. Instead, based on the previous investigation of the compressive strength of the fly ash trackbed material [3], the maximum load of 15 kN (2 MPa) was adopted for this research. The loading was applied in five steps with the maximum load of 3, 6, 9, 12 and 15 kN respectively and 100 cycles of loading were performed in each step. The applied loading force measured during the experiment for a representative sample is shown on Figure 2.

2.2. Instrumentation of the laboratory experiment

The testing of the samples was performed with a loading frame Inova Praha ZUZ 200 1350 with the maximal dynamic load of 160 kN. The contraction of the samples in the vertical direction was measured along the samples by means of three absolute LVDT sensors of displacement Ahlborn FWA025T [12]. In accordance with ČSN EN 13286-43 [8], the displacement sensors were installed in between two metal rings fixed to the top and the bottom of the sample. The applied force as well as the vertical displacement were stored in Ahlborn Almemo 2690-8A data logger [13]. The sampling rate of 20 samples per second was chosen for the data storage, which is the maximum available rate the data logger can provide. The experiment set up is show on Figure 3.

3. Results and discussion

In this paper, only preliminary results of the research are presented. Hence, only results for a representative sample are shown.

Figure 4 shows the measured vertical displacement for all three LVDT sensors. It can be seen that with increasing force the displacement increases into negative values, i.e. the sample contracts. Sensors 1 and 2 seem to be in agreement but Sensor 3 seems to not follow the anticipated trend. The discrepancy may be explained by the method used to fix the steel rings to the samples during the experiment. The rings were fixed to the samples by rectifying screws. Even though the screws had pointed tip, as the cyclic loading progressed, it was observed that the screws were becoming loose and the rings deviated from its original positions slightly. Despite the absolute value measured by Sensor 3 does not have a significant impact on the mean value used for further evaluation, the inconsistency needs to be investigated further in order to refine the applied methodology. Figure 5 shows the mean value of displacement calculated from all three sensors, which is used for further investigation.

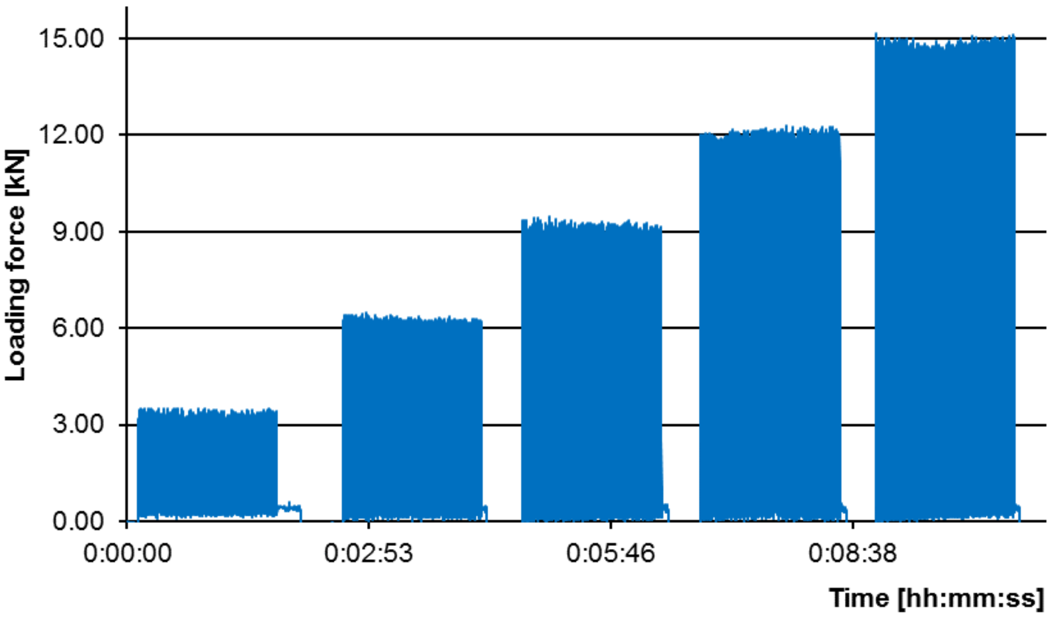

Figure 2. Loading force for the representative sample.

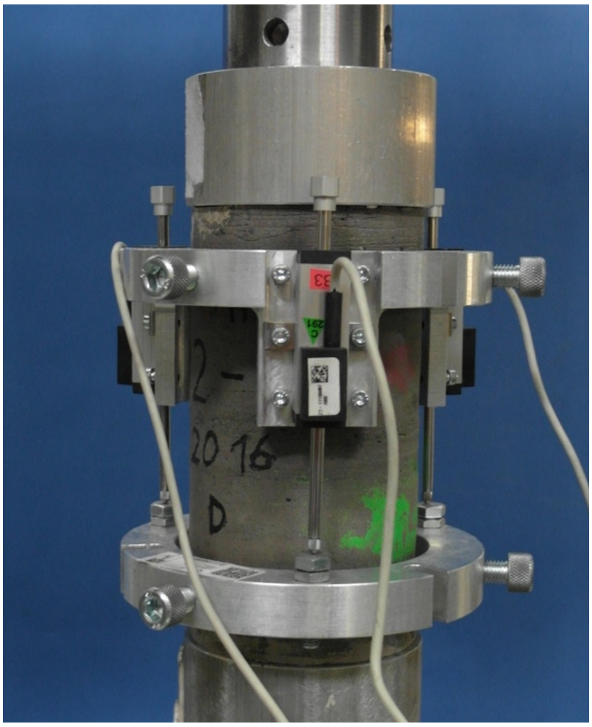

Figure 3. Instrumentation used during the experiment.

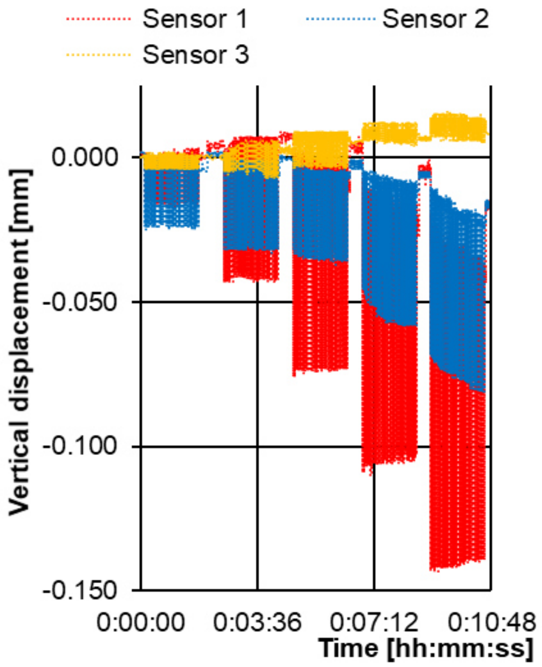

Figure 4. Measured displacement for the representative sample.

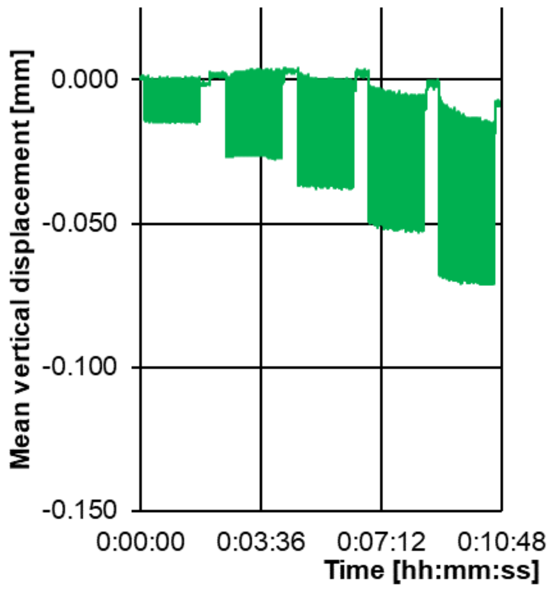

Figure 5. Mean value of displacement for the representative sample.

The applied uniaxial stress in the sample was calculated using the force from Figure 2 and the geometry of the sample. Similarly, the applied strain was calculated using the mean value of displacement from Figure 5. The resulting stress and stain were combined to plot hysteresis loops of the loading cycles on Figure 6.

It can be seen on Figure 6 that hysteresis loops for Step 1 and Step 2 appear quite stable, neither changing their shape nor move in the stress-strain space. This suggests close to pure elastic behaviour of the sample in Steps 1 and 2 of the loading For Steps 3, 4 and 5 it can be seen that the shape of the hysteresis loops is becoming more convex, which is a characteristic change with increasing non-linearity [14]. Also, there is clearly visible ratcheting for Steps 3-5 and the rate of ratcheting seems to increase with the increasing load, which again suggests increasing non-linearity. From Figure 6 it can be derived that the elastic limit for the representative sample is approximately 1000 kPa.

The elastic modulus E was calculated for every loading cycle as a secant modulus with the strain at the end of the loading cycle being adjusted for the influence of the permanent strain. The change of the elastic modulus with the increasing number of cycles of loading is presented on Figure 7.

It can be seen from Figure 7 that for the first two steps of loading the value of the modulus lies between 6000-6500 MPa, a slightly lower value than the value for the remaining steps, which approaches 7000 MPa. The ratcheting is also visible, especially for the last step of loading.

The last investigated characteristic was the evolution of permanent deflection, presented on Figure 8. Due to the anticipated movement of the steel ring (above) it was only possible to calculate the value of permanent strain which is added to the total permanent strain in each loading cycle. Hence, it should be noted that the figure does not show total permanent strain but only its rate.

It can be seen from Figure 8 that the absolute measurement of the permanent strain approaches the resolution limits of the Ahlborn FWA025T sensors. However, when linear trend is calculated from the measured data, the evolution of the permanent strain is practically zero for the first three steps. A non-zero evolution of permanent strain can be observed for Step 4 and 5. Also, the trend for the last two steps decreases, which corresponds well with the ratcheting behaviour observed from the hysteresis loops on Figure 6. The combination of results on Figures 6 and 8 suggests that the last three steps lie in the non-elastic area but under the shakedown limit. Hence, the shakedown limit of the representative sample is higher than 2000 kPa for the representative sample.

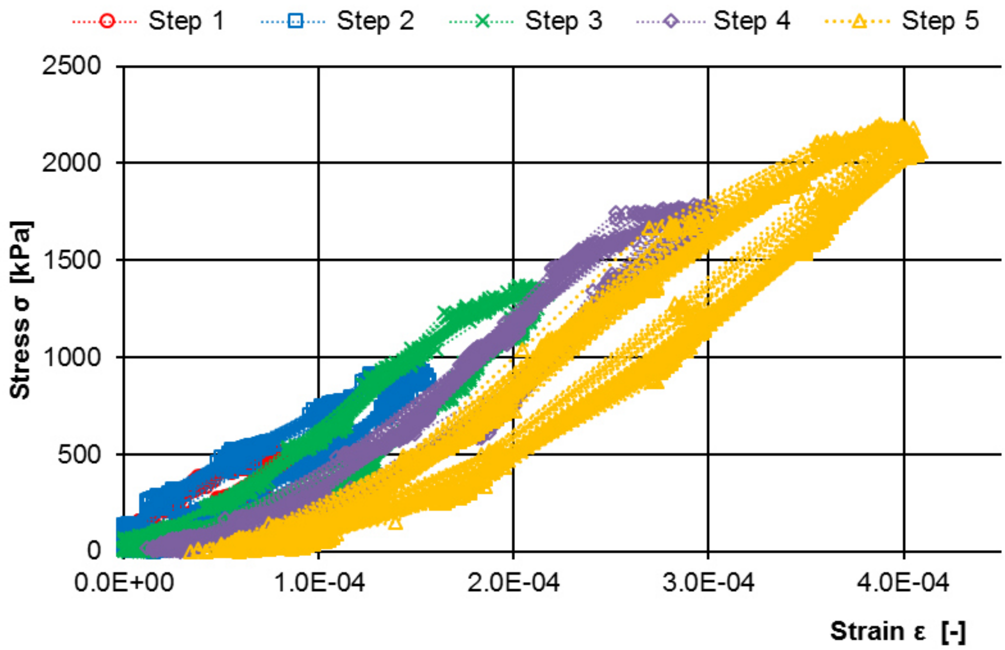

Figure 6. Hysteresis loops for cyclic loading of the representative sample.

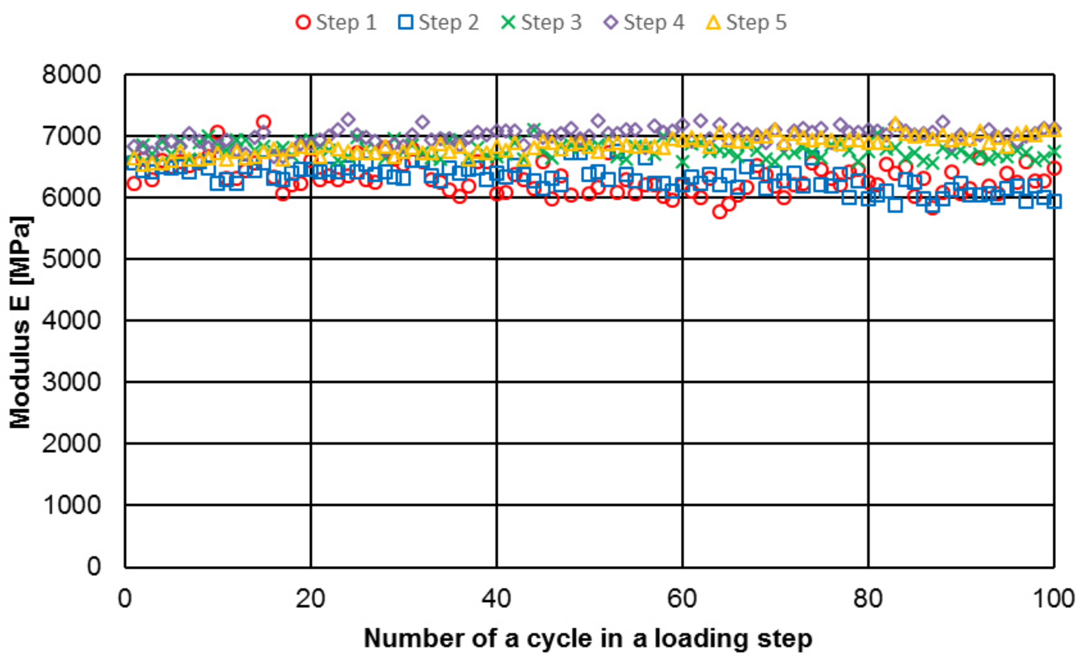

Figure 7. Evolution of the elastic modulus with cycling for the representative sample.

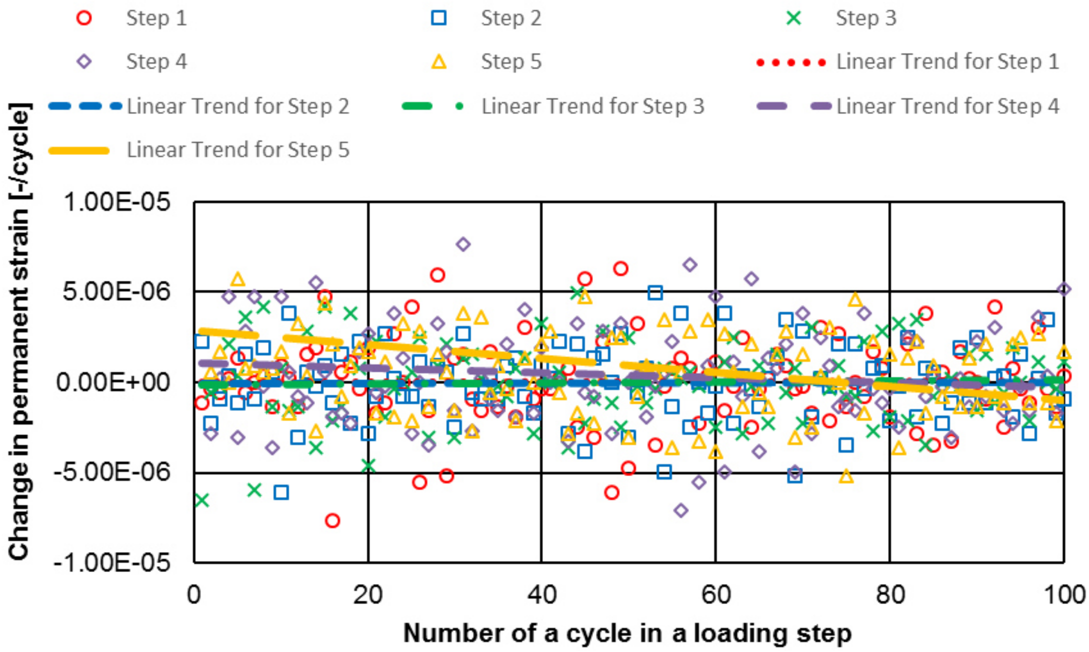

Figure 8. Evolution of the rate in permanent strain for the representative sample.

4. Discussion and Conclusions

In this paper, recent results from the investigation of the behaviour of fly ash trackbed material subjected to cyclic dynamic loading were presented. The methodology adopted for the investigation was discussed and the preliminary results of the investigation for the representative sample of the material were shown. From the presented results, the following conclusive remarks can be made:

For the methodology:

- The fixing of the steel rings to the sample via the rectifying screws shall be further refined to minimize the movement of the rings as the experiment progresses.
- The adopted maximum load of the last cycle seems to lie above the elastic limit, hence it allows to investigate some non-linear properties of the material. However, the load seems to lie below the shakedown limit, which might be important for limit analysis [9]. For this reason, it is recommended to apply additional loading steps until the failure of a sample is reached.
- For similar reasons as above, it is recommended to further investigate the failure point of the sample by continuing the cyclic loading in the last step until the failure of the sample
- The adopted instrumentation does not seem to be sufficient for the measurement of the absolute value of permanent contraction/strain.
- The maximum sampling rate of the data logger used requires significant changes to be made to the loading sequence. In order to use the loading frequency as suggested in e.g. AASHTO T307 a data logger with minimum sampling rate of 100 Hz should be used.

For the behaviour of the fly ash trackbed material:

- The material behaves non-linearly when dynamic loading exceeds the elastic limit.
- The material exhibits ratcheting in the non-linear area. The rate of ratcheting increases with increasing loading.
- The elastic limit for the representative sample seems to be approximately 1000 kPa.

- The elastic modulus of the representative sample lies between 6000-6500 MPa for loading in the elastic area and approaches 7000 MPa for loading in the non-linear area.

For future research, it is recommended to further refine the methodology of the experiment, as suggested above, so that the methodology can be applied on statistically representative number of samples.

Acknowledgements

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